Next generation of IACT arrays:
scientific objectives versus energy domains

Felix Aharonian
Max-Planck-Institut für Kernphysik
Saupfercheckweg 1, 69117 Heidelberg, Germany

Several key motivations and perspectives of ground based gamma-ray astronomy are discussed in the context of the specifics of detection techniques and scientific topics/objectives relevant to four major energy domains – very-low or *multi-GeV* ($E \leq$ 30 GeV), low or *sub-TeV* (30 GeV - 300 GeV), high or *TeV* (300 GeV - 30 TeV), and very-high or *sub-PeV* ($E \geq 30$ TeV) intervals – to be covered by the next generation of IACT arrays.

1 Introduction

The recent success of ground-based gamma-ray astronomy, in particular the exciting discoveries of many new galactic and extragalactic TeV γ-ray emitters by *HESS* (see e.g. Ref. [1]), elevated the status of the field from an "astronomy with several sources" to the level of truly observational discipline. In addition to the important astrophysical and cosmological implications, these results will have a considerable impact on plans of the gamma-ray community towards the next generation of Imaging Atmospheric Cherenkov Telescope (IACT) arrays. One of the principal issues in this regard is the choice of the energy domain. The imaging of air showers with atmospheric Cherenkov telescopes [2–9], especially in the stereoscopic mode is a powerful detection technique [10–12] which (potentially) allows coverage of a broad energy range extending from ≤ 10 GeV to ≥ 100 TeV γ-rays [1].

If one limits the energy region to a relatively modest threshold around 100 GeV, the performance of the telescope arrays and their implementation can be predicted with confidence. Therefore it was quite natural that in the mid 1990s the stereoscopic IACT arrays consisting of 10m-diameter class reflectors were recognized, among a variety competing designs, as the most effective approach that could facilitate a qualitative improvement in performance at an affordable cost and with a guaranteed fast scientific return [11]. This choice was soon accomplished in the form of the *HESS* 4-telescope (Phase-1) array. The results obtained during the first two years of operation

[1] Note that the first attempt of stereoscopic observations of air showers in the early 1970s using the so-called "double-beam" method [13] actually contained (indirectly) also some elements of the modern imaging Cherenkov technique.

of this array fully support the most optimistic predictions concerning both the instrumental performance and the astrophysical implications, in particular, the high quality morphological and spectrometric studies of extended galactic regions in TeV γ-rays. It is expected that together with two other similar projects - *CANGAROO-III* [14] and *VERITAS* [15], as well as the *MAGIC* system consisting of two 17m-diameter telescopes [16], the *HESS* (Phase-1) array will dominate the field for the next several years (see e.g. Ref. [17]). At the same time, the great success of *HESS* supplies a strong rationale for the next generation IACT arrays.

2 Planning future IACT Arrays

The ultimate goal in planning of the next generation IACT arrays should be a dramatic (down to the level of $10^{-14}\ \mathrm{erg/cm^2 s}$) improvement of the flux sensitivity in the classical/standard (0.1-10 TeV) energy regime, and an aggressive expansion of the energy domain of IACT arrays in two directions - down to (multi)GeV energies and up to (sub)PeV energies. In this regard, I believe that the design studies of future IACT arrays will proceed in four independent, although tightly correlated and complementary directions with an ambitious aim to cover (more or less) homogeneously a very broad energy range extending from ≤ 0.03 TeV (30 GeV) to ≥ 300 TeV (0.3 PeV). Below I discuss some basic requirements in the following four energy regimes in the context of detection specifics and principal scientific issues to be addressed by future IACT arrays:

- very-low or **multi-GeV** : $\leq$ 30 GeV
- low or **sub-TeV** : 30 GeV - 300 GeV
- high or **TeV** : 300 GeV - 30 TeV
- very-high or **sub-PeV** : $\geq$ 30 TeV

2.1 TeV Regime: $10^{-14}\ \mathrm{erg/cm^2 s}$ *sensitivity IACT Arrays*

This is the most natural/intrinsic for the IACT technique energy regime, where the combination of three basic factors – (i) the high efficiency of detection/identification of electromagnetic showers, (ii) good accuracy of reconstruction of the direction and energy of primary γ-rays, and (iii) the large γ-ray photon statistics – allows the best energy flux sensitivity at the level of $10^{-14}\ \mathrm{erg/cm^2 s}$ (≈ 0.3 milliCrab at 1 TeV), and angular resolution $\delta\theta \approx$ 1-2 arcminutes. This can be achieved by stereoscopic arrays consisting of multi (up to 100 or so) 10m-diameter class (HESS-type) telescopes.

The flux sensitivity $10^{-14}\ \mathrm{erg/cm^2 s}$ at TeV energies would be a great and impressive achievement even in the standards of the most advanced branches of observational astronomy. This should allow us to probe the γ-ray luminosities of potential TeV emitters at the levels of $10^{32} (d/10 \mathrm{kpc})^2\ \mathrm{erg/s}$ for galactic sources and

$10^{40}(d/100\mathrm{Mpc})^2\ \mathrm{erg/s}$ for extragalactic objects. Although for moderately extended sources, e.g. of angular size $\Psi \sim 1^\circ$, the minimum detectable energy flux will be by a factor of $\Psi/\delta\theta$ ~10-30 higher, yet it would be better than the energy flux sensitivities of the best current X-ray satellites, *Chandra*, *XMM*-Newton and *Suzaku*, in the keV band, i.e. should allow the deepest probes of nonthermal high energy phenomena in extended sources, in particular in shell type Supernova Remnants (SNRs), Giant Molecular Clouds (GMCs), Pulsar Driven Nebulae (Plerions), Clusters of Galaxies, hypothetical Giant Pair Halos around AGN, *etc.*

Therefore, one of the prime objectives and urgent issues of ground-based gamma-ray astronomy in the foreseeable future should be the design and construction of a "$10^{-14}\ \mathrm{erg/cm^2s}$ *sensitivity IACT Array*". Since this will be essentially a TeV instrument with a limited capability for study of extragalactic objects located beyond z =0.2-0.3, but with a great potential for morphological and spectrometric measurements and deep surveys, this array should be dedicated, first of all, to studies of galactic sources and the diffuse emission of the Galactic Disk.

The $10^{-14}\ \mathrm{erg/cm^2s}$ flux sensitivity and $\geq 5^\circ$ FoV should provide very deep surveys of the Galactic Disk, as well as of some selected regions above the Galactic Plane. One may predict, based on the extrapolation of *HESS* results, that such an instrument should discover and resolve hundreds, or perhaps even thousands of galactic TeV sources. In particular, this array should allow statistically significant detection of the weakest *HESS* sources for exposure times less than 1 hour, and, more importantly, detailed studies of spectral and spatial structures of relatively strong (≥ 1 milliCrab) *HESS* sources. This could provide key insight into the origin of Galactic Cosmic Rays (GCRs), in particular decisive tests for the hypothesis that shell type SNRs are responsible for the *bulk* of observed cosmic rays up to $10^{15}\ \mathrm{eV}$. Although several shell type SNRs already have been reported as TeV emitters, and in all cases the TeV emission can be explained quite naturally by hadronic (pp) interactions, the limited information about both the spectral and spatial distributions of detected signals does not allow definite conclusions concerning the nature of TeV emission, especially because the latter could be substantially "contaminated" by γ-rays of leptonic (inverse Compton) origin. Moreover the evidence of the hadronic origin of TeV emission from a few selected SNRs does not yet imply that the bulk of GCRs can be explained by shell type SNRs. The discovery *by HESS* of TeV γ-rays from several plerions and two binary systems (of different origin) indicates that other galactic sources, in particular pulsars/pulsar-winds and microquasars, may contribute comparably to the flux of locally observed cosmic rays.

While young particle accelerators can be identified directly, i.e. through their characteristic γ-ray emission, in the case of old sources in which the particle acceleration has ceased and the most energetic (TeV and PeV) particles have already left the source, the TeV γ-ray emission should be significantly suppressed. On the other

hand, one may expect detectable TeV γ-ray emission from interactions of *run-away protons* with the nearby dense environments. Giant Molecular Clouds (GMCs) with diffuse masses 10^4 to 10^6 $\mathrm{M}_\odot$, seem to be ideal objects to serve as effective targets. These objects are intimately connected with star formation regions that are strongly believed to be the most probable locations (with or without SNRs) of cosmic ray production in our Galaxy. The search for TeV photons from GMCs is important to ascertain the possible existence of nearby high energy proton accelerators. Remarkably, 10^{-14} $\mathrm{erg/cm^2s}$ sensitivity should allow detection of TeV gamma-ray emission not only from GMCs located close to young particle accelerators, but also from "passive clouds" located in ordinary sites of interstellar medium, far from active accelerators. Such clouds can serve as unique "barometers" for measuring the pressure (energy density) of protons of the sea of GCRs in different parts of the Galactic Disk. Since the hadronic component of the diffuse γ-ray background is essentially contributed by individual clouds, the potential of the 10^{-14} $\mathrm{erg/cm^2s}$ sensitivity arrays to resolve the small-scale ($\sim 0.1°$) features in the form of individual γ-ray emitting clouds, and thus to study the variations of GCRs on ~ 10 to 100 pc scales, would be crucial for understanding of many aspects of the origin and propagation of galactic cosmic rays.

This array will be a very effective tool also for spectrometric and temporal studies of highly variable phenomena in compact galactic objects like microquasars, as well as Sgr A* - presumably a Supermassive Black Hole in the center of our Galaxy. To a large extent this concerns also relatively nearby ($z \leq 0.1$) extragalactic sources, in particular BL Lac objects. In this regard one may predict the discovery of numerous BL Lacs, although with significantly absorbed TeV spectra.

Another aspect of extragalactic studies, with a promise for exciting findings, is connected to the search for several components of TeV radiation from different parts (compact cores, kpc-scale jets, radio lobes) of two nearby radiogalaxies, M87 and Cen A, as well as from luminous starburst galaxies like Arp 220. Finally, this array should detect TeV γ-ray emission expected from nearby clusters of Galaxies, like the Virgo and Coma clusters, unless our current understanding of the nonthermal energy budgets and acceleration processes in these unique cosmological reservoirs of cosmic rays is completely wrong. It is clear, however, that because of the severe intergalactic absorption of TeV γ-rays, many extragalactic and cosmological topics of gamma-ray astronomy can be addressed adequately by lower energy-threshold instruments.

2.2 Sub-TeV Regime: *Very Large Aperture IACT Arrays*

The energy threshold $\varepsilon_{\rm th}$ of IACTs is generally defined as a characteristic energy at which the γ-ray detection rate for a primary power-law spectrum with photon index Γ =2-3 achieves its maximum. It is well known, from Monte Carlo simulations and from the operation of previous generation IACTs, that in practice the best per-

formance, in particular the minimum detectable energy flux, is achieved at energies exceeding several times $\varepsilon_{\rm th}$. In this regard, for optimization of γ-ray detection around 100 GeV, one should reduce the energy threshold of telescopes to $\varepsilon_{\rm th} \leq 30\ \rm GeV$. This can be done by using very large, ≥ 20 m-diameter class reflectors and/or very high ($\geq 40\%$) quantum efficiency fast (ns) optical receivers. On the other hand, reduction of the detection threshold to such low energies is an important scientific issue in its own right; the intermediate interval between 30 and 300 GeV is a crucial energy regime for certain class of galactic and extragalactic γ-ray source populations.

Within the next two years a stereoscopic system consisting of two MAGIC 17m-diameter telescopes [18], will start to take meaningful probes from this important energy band. In a more distant future, this energy region can be comprehensively explored by the *HESS* and *MAGIC* collaborations using 30m-diameter class telescope arrays; presently two prototypes of such extremely big telescopes are in the construction [19] or design-study [18] stages.

In order to achieve the lowest possible energy threshold, the integration time of the Cherenkov light should be reduced to ≤ 10 ns. Coupled with the requirement of high quality imaging, this constrains the choice of possible configurations of 30m-diameter class optical reflectors, and correspondingly limits the FoV to $\sim 3^\circ$. While for point-like sources this is not a big disadvantage, it limits significantly the capability of these telescopes for studies of extended sources. Also, it limits the γ-ray detection area at high energies. Therefore, the optimization of the performance for point-like sources in the energy range below 1 TeV should be a key issue in design studies of future 30m-diameter telescope arrays. In this sense the 30m-diameter class IACT arrays can be considered as essentially sub-TeV instruments.

There are several reasons to believe that the energy regime below 100 GeV should be prolific in number of γ-ray sources, especially when the flux sensitivities of IACT arrays in this energy band achieve the level close to $10^{-13}\ \rm erg/cm^2 s$. From a purely phenomenological perspective, TeV (*HESS*) and GeV (*EGRET*) sources are expected to show up in the immediate neighbor region between 10 and 100 GeV, even in the case of significant hardening of the spectra of TeV sources at lower energies, or strong steepening of GeV sources at higher energies. In particular, because of energy-dependent escape of protons and electrons, as well as severe radiative losses of ultrarelativistic electrons, one may expect much steeper spectra of particles inside old objects compared to young, typically 1000 yr old accelerators. If so, the major fraction of galactic accelerators should have steep proton spectra, and therefore higher chances to be detected in γ-rays at energies below ≤ 100 GeV.

The γ-ray sources with steep energy spectra should dominate, although for different reasons, e.g. due to the intergalactic and internal photon-photon absorption, also in extragalactic source populations. Therefore, while several blazars with very steep energy spectra have been detected by *HESS* after significant efforts (long exposure

times), they should be detected much easier at energies below 100 GeV. Thus, in this energy band we may expect a dramatic increase of the number of detectable blazars up to redshifts $z \sim 1$.

Generally, the 30-300 GeV and 300 GeV-30 TeV energy bands share many common phenomena and sources. In this regard, the studies below 100 GeV are complementary, in some cases even crucial, for understanding the origin of γ-ray emission. For example, the spectral measurements in this energy interval may provide decisive information whether the TeV emission from shell type SNRs and plerions has inverse Compton (very hard energy spectra at low energies, with gradual steepening above 1 TeV) or π^0-decay (typically single power-laws throughout the 10 GeV to ≥ 10 TeV interval) origin. Another example. In compact leptonic sources (e.g. in binary systems) one should expect transition of the process of γ-ray production from the Thompson to the Klein-Nishina regime or (in the case of binaries with very luminous optical companion stars) from optically thin (at GeV energies) to optically thick (at TeV energies) regimes. The corresponding characteristic spectral features in the 10 GeV to 1 TeV interval can serve as distinct signatures of γ-ray production regions.

2.3 Sub-PeV Regime: *10km^2 IACT Arrays*

The current trend to reduce the energy threshold of ground-based detection technique concerns both the atmospheric Cherenkov telescopes and the air-shower (particle detector) arrays. As a result, presently there is only little instrumental activity in the energy domain above 30 TeV. The general tendency of decreasing γ-ray fluxes with energy becomes especially dramatic above 10 TeV. The reasons could be different, e.g. external and internal absorption of γ-rays, limited efficiency of particle acceleration processes, escape of highest energy particles from the production region, *etc.* This limits the capability of traditional air-shower arrays, mainly because of the limited proton/gamma separation power, limited angular resolution and limited detection areas. Any meaningful study of cosmic γ-rays beyond 30 TeV requires detection areas exceeding $1 \ \mathrm{km}^2$. At large zenith angles, 60° or so, the collection area of the atmospheric Cherenkov detectors increases rapidly. Thus the use of IACT systems at large zenith angles can improve the γ-ray statistics in the multi-TeV or sub-PeV region. For many astrophysical objects, on the other hand, the observation time in this mode is quite short (because the sources set rapidly below the horizon). Besides, even small variations of the atmospheric transparency add non-negligible uncertainties in the derivation of shower parameters obtained at large zenith angles.

An effective and straightforward approach would be the use of IACT arrays optimized for detection of γ-rays in the 30 to 300 TeV region. Such an array can consists of rather modest, approximately 20 to 50 m^2 area reflectors separated from each other, depending on the scientific objectives and the configuration of the imagers, between

300 to 500 m. The requirement to the pixel size of imagers is also quite modest, between $0.25°$ to $0.5°$, however they should have large FoV $\geq 5°$ in order to detect showers from distances ≥ 300 m. It is expected that an array consisting of several tens of such telescopes can provide an extraordinary large detection area of about $10\ \mathrm{km}^2$, reasonable efficiency for suppression of hadronic showers, very good angular resolution of few arcmin and quite good, better than 0.15%, energy resolution [20].

Although the prime motivation of such an array is the energy region above 30 TeV, it can serve as an extremely powerful tool for detailed spectrometric and morphological studies of lower (3 to 10 TeV) energy γ-rays as well. In particular, all *HESS* sources with hard energy spectra extending beyond several TeV, would be perfect targets for studies with unprecedented TeV photon statistics.

But, of course, the highest priority scientific topics for such an instrument are linked to the search and studies of "Cosmic PeVatrons" and the surrounding regions. This concerns, first of all, galactic sources, in particular the shell type SNRs, Molecular Clouds, Pulsar Wind Nebulae and Microquasars. For example, the detection of ≥ 30 TeV γ-rays from shell type SNRs would be direct proof that the shocks in SNRs accelerate protons up to energies 10^3 TeV. While one may hope to have only handful SNRs detected at energies above 30 TeV, namely the youngest ones of age less than ≈ 1000 year, the chances to detect γ-rays well beyond 10 TeV are significantly higher for molecular clouds located nearby the Galactic PeVatrons. Because of the (suspected) slow diffusion of charged particles in turbulent environments in star formation regions, where the cosmic accelerators appear most frequently, we should expect "delayed" emission from interactions of cosmic rays, which left their production sites (accelerators) some time ago, with nearby dense molecular clouds. The energy spectra of secondary γ-rays strongly depend on the diffusion coefficient of charged particles, the age of the accelerator, and the distance between the accelerator and the cloud. For some combinations of relevant parameters (young source and/or slow diffusion and/or distant clouds), one may expect extremely hard γ-ray spectra with a maximum (in the νF_ν plot) beyond 10 TeV.

The synchrotron nebulae initiated by termination of relativistic pulsar winds, where particles can be accelerated to much higher energies than in shell type SNRs, are expected as another prolific class of multi-TeV and sub-PeV emitters.

Because of severe intergalactic absorption one may expect $\geq$ 30 TeV γ-rays only from a handful extragalactic sources like radiogalaxies Cen A and M87, as well as from some nearby starburst and normal galaxies. Although the sub-PeV IACT arrays should be dedicated for galactic studies, the detection of ≥ 30 TeV γ-rays from nearby extragalactic objects would have, among other astrophysical implications, a great cosmological importance for probing the far-infrared cosmic background. The distances to these objects perfectly match the γ-ray astronomical method of deriving information about the cosmic infrared background radiation at $\geq 30\mu$ wavelengths.

2.4 Multi-GeV Regime: *Gamma-Ray Timing Explorers*

One of the greatest expectations of gamma-ray astronomy is connected with the launch of *GLAST*. This instrument, with a nice performance between 30 MeV to 10 GeV, allows also an extension of study of the γ-ray sky to 100 GeV. Thus the gap between space-based and ground-based instruments will finally disappear. Generally this is considered as one of the major achievements of observational gamma-ray astronomy. Although certain technical (cross-calibration of instruments) and scientific (broad band γ-ray coverage) aspects of this issue are quite important, the astrophysical significance of the expected overlap of detection domains of GLAST and the current ground-based instruments seems somewhat overemphasized in the literature. Although at GeV energies *GLAST* will improve the *EGRET* sensitivity by almost two orders of magnitude, the capability of *GLAST* and, in fact, of any post-GLAST space project at energies beyond 10 GeV will be quite limited, first of all because of the limited detection area, unless the Moon would be used in (far) future as a possible platform for installation of very large, $\geq 100 \ \mathrm{m}^2$ area pair-conversion detectors. It is clear that the space-based resources of GeV gamma-ray astronomy have achieved a point where any further progress would appear extremely difficult and very expensive. For the next decades to come there is no space-based mission planned for the exploration of the gamma-ray sky.

The impressive sensitivity of *GLAST* at 1 GeV - few times $10^{-13} \ \mathrm{erg/cm^2 s}$ - can be achieved after one year all-sky survey. While for the persistent γ-ray sources this is an adequate estimate of the performance (taking into account that a huge number of sources will be simultaneously monitored by the large, almost $\sim 2\pi$ steradian homogeneous FoV), the small, $\approx 1 \ \mathrm{m}^2$ detection area limits the potential of this instrument at GeV energies for detailed studies of the temporal and spectral characteristics of highly variable sources like blazars or solitary events like gamma-ray bursts (GRBs). In this regard, the need for a powerful multi-GeV instrument to study transient phenomena with adequate high energy γ-ray photon statistics, has motivated the idea/concept to extend of the domain of the imaging atmospheric Cherenkov technique, with its huge collection area $\geq 10^4 \ \mathrm{m}^2$, down to energies of about 5 GeV. In practice, this can be achieved with a stereoscopic telescope system consisting of several ≥ 20m diameter dishes located at high elevations of the order of 5 km above sea level. That is why the concept was called 5@5 [21]. The successful realization of such an instrument largely depends on the availability of sites with a dry and transparent atmosphere at an altitude as high as 5 km. Nature does provide us with such an extraordinary site - the Atacama desert in Northern Chile which has been chosen for the installation of one of the most powerful future astronomical instruments – the Atacama Large Millimeter Array (ALMA). Several good sites for installation of high-altitude multi-GeV telescope arrays exist also in the Northern Hemisphere, e.g.

in India (Hanle, 4.2km asl) [22].

Another approach to achieve a sub-10 GeV energy threshold, but at more comfortable altitudes, is linked to very large aperture, 30m diameter telescopes equipped with novel high quantum efficiency receivers. Clearly, the combination of 3 key elements – high altitude, large optical reflectors, and high quantum efficiency focal plane receivers – would be an ideal combination for construction of γ-ray detectors with an energy threshold as low as several GeV.

Dramatic reduction of the energy threshold of detectors is a key issue for a number of astrophysical and cosmological problems, e.g. for study of γ-radiation from pulsars and cosmologically distant objects like quasars and GRBs. The spectra of typical representatives of all three source populations contain, for different reasons, sharp energy cutoffs around or below 10 GeV. That is why the *uncompromised* reduction of the energy threshold of detectors down to several GeV is so critical, and would justify the choice of such uncomfortable altitudes for operation of large IACT arrays.

The concept of 5@5 is not only motivated by the possibility of coverage of the yet unexplored region of multi-GeV γ-rays. In fact, 5@5 combines two advantages of the current ground-based and satellite-borne γ-ray domains - large photon fluxes and enormous detection areas. This would make the 5@5 a unique *Gamma-ray Timing Explorer* (with a sensitivity to detect the hard-spectra EGRET sources in exposure times of seconds to minutes) for the study of transient non-thermal γ-ray phenomena like rapid variability of Blazars, synchrotron flares in Microquasars, the high energy (GeV) counterparts of Gamma Ray Bursts, *etc.*.

If the spectra of GRBs extend to high energies, which is the case at least for some of GRBs, then the sensitivity of 5@5 should allow detailed studies of spectral and temporal features of GRBs in this extremely important energy band. The detection of ≥ 5 GeV episodic events with typical GRB fluxes $\geq 10^{-8}\,\mathrm{erg/cm^2 s}$ (at keV-MeV energies) would require $\leq 1\,\mathrm{s}$ observation time. Thus it would be possible to monitor the spectral evolution of GRBs on very short, sub-second timescales. Remarkably, even for fluxes as low as $10^{-10}\,\mathrm{erg/cm^2 s}$, the required detection time does not exceed 100 sec. Some of the GRB models predict multi GeV emission during the afterglow phase of evolution. If so, 5@5 could serve as a unique tool for studies of the properties of GRBs at late stages of their evolution, and thus provide a key information about these most mysterious objects in the Universe.

The capability of 5@5 is not limited by variable source studies. This instrument, in fact, will have significantly broader goals related to detailed spectrometry in the multi-GeV energy band of γ-ray sources like SNRs, pulsars, unshocked pulsar winds, perions, large (kpc) scale extragalactic jets, clusters of galaxies, *etc*. For example, the direct searches for pulsed GeV radiation from a fraction of unidentified EGRET sources (suspected to be pulsars) without invoking information from the longer (radio, optical, X-ray) wavelengths, seems to be an important issue, especially because in

many pulsars the periodic signals at low frequencies could be suppressed.

Finally, the reasonably good energy resolution in the energy interval between 10 and 100 GeV, coupled with adequate gamma-ray photon statistics, is crucial for effective cosmological studies through (1) probing the cosmological evolution of the cosmic background radiation at optical and UV wavelengths, (2) detecting γ-rays from large scale structures (Galaxy Clusters) , and (3) searching for characteristic emission from the non-baryonic Dark Matter Halos.

3 Discussion

Different classes of IACT arrays described above are characterized by certain energy intervals in which the best energy flux sensitivity is achieved. These "best performance energy intervals" can be grouped in the following segments : $\leq 30\ \mathrm{GeV}$ (*multi-GeV* band), 30 GeV - 300 GeV (*sub-TeV* band), 0.3 TeV to 30 TeV (*TeV* band), and $\geq 30\ \mathrm{TeV}$ (*multi-TeV* or *sub-PeV* band), respectively. It should be noted, however, that all four versions of IACT arrays allow effective γ-ray detection in significantly broader intervals, namely each of them covers at least 2 decades in energy. Thus the energy domains of these arrays largely overlap. Since all 4 versions of IACT arrays contain, from instrumental perspectives, the same basic elements, and generally have common scientific motivations, an ideal arrangement would be the combination of the *sub-TeV, TeV,* and *sub-PeV* (sub)arrays in a single array with a quite homogeneous coverage (in the sense of performace) throughout the energy region from approximately 30 GeV to 300 TeV. The high γ-ray detection rates, coupled with good angular and energy resolutions over four energy decades would make these combined arrays as multi-functional and multi-purpose Ground Based Gamma-Ray Observatories (GBGROs) with a great capability for *spectrometric*, *morphological* and *temporal* studies of a diverse range of persistent and transient high energy phenomena in the Universe. There is little doubt that the construction of such observatories, desirably (at least) one in the Southern and another in the Northern Hemispheres, will lead to many unique results and exciting discoveries. The sites should have good optical conditions and optimal, close to 2km asl, altitudes[2]. The *HESS* site in Namibia, as well as the site of the Pierre Auger Cosmic Ray Observatory in Argentina in the Southern Hemisphere, and several sites in Northern Hemisphere (e.g. in Arizona (USA), Canary Islands La Palma or Tenerife, *etc.*) match well these requirements.

The *sub-TeV* (sub)arrays of future GBGROs with adequate performance require deeper design and technological studies, albeit some 30m diameter class prototype

[2]Actually this should be considered as a *compromised* rather than an optimal altitude, taking into account that while 2km elevation is optimal for TeV measurements, for sub-TeV and multi-TeV (sub-PeV) energy bands higher (more than 3km) and lower (close to the sea level) elevations are more favorable.

telescopes are expected already in the foreseeable future, in particular as integrates of the plans of enlargement of the *HESS* [19] and *MAGIC* [18] arrays. The operation of these single dishes will provide, together with GLAST, the first reasonably deep probes of the sky in the yet unknown sub-100 GeV energy region.

The main issue of realization of the "10 km^2" *sub-PeV* (sub)arrays, seems to be related to the production of relatively cheap imagers with large FoV exceeding $5°$. On shorter timescales, it would be important to build an independent sub-PeV array in the Southern Hemisphere, e.g. in Australia which has suitable sites at low (close to the sea level) altitudes which are beneficial in terms of collection areas for ≥ 10 TeV observations. Such an array consisting of large number of small aperture telescopes will be a powerful instrument in its own right (designed for the discovery of "Cosmic PeVatrons"), *the fast scientific return of which seems to be quite secure, given the extension of energy spectra of many HESS sources beyond several TeV.*

While all energy bands of future GBGROs are equally important and complementary, the highest priority and preference (in terms of the order of accomplishment) should be given (in my view) to the $10^{-14}\ \mathrm{erg/cm^2 s}$ sensitivity *TeV (sub)arrays*. One may predict with confidence that the construction of such a powerful detector, which can be treated as a scaled-up version of the current *HESS* array, could be completed without unexpected complications on relatively short timescales. Such an array does not require technological innovations, and relies on the approach, the reliability and feasibility of which have been clearly demonstrated, although on smaller scales, by the *CANGAROO*, *HESS*, *MAGIC*, and VERITAS collaboration. In order to reduce the energy threshold to ≈ 30 GeV and thus to improve the flux sensitivity around 100 GeV, one may consider somewhat larger, e.g. 15m diameter class telescopes (but without compromising the field of view, which should be as large as $5°$), installed at somewhat higher, 3 to 4 km elevations [24]. There are several suitable sites for such observatories in both Hemispheres, in particular in northern Argentina and Chile. Two very attractive aspects of this option of a GBGRO should be emphasized: (1) *a very broad, from 30 GeV to 30 TeV energy region can be covered by a single array of identical telescopes with relatively modest optical reflectors, equipped with conventional PMT-based imagers, and installed at high but still comfortable altitudes*, and (2) *the design and construction of such a GBGRO can begin right now*.

Although one may suggest to extend the energy domain of these GBGROs down to ≤ 10 GeV, e.g. by adding 30m diameter class reflectors and/or using high ($\geq 50\%$) quantum efficiency imagers, I believe that the projects of future multi-GeV arrays should proceed through independent studies, given the technological challenges (operation of large telescopes in robotic regime at high altitudes, construction of high quantum efficiency focal plane imagers, *etc.*). Because of very specific astrophysical and cosmological goals, in particular the importance of the studies of highly variable

γ-ray phenomena in the remote Universe (e.g. quasars, GRBs, *etc.* at $z \geq 5$), the reduction of the energy threshold to the lowest possible level is the key issue for these *Gamma-Ray Timing Explorers*. That is why I believe that this activity should proceed through the concept of 5@5. The successful realization of a high-altitude IACT array *during the lifetime of GLAST* would be, of course, a great achievement of observational gamma-ray astronomy [23]. GLAST and 5@5 are highly complementary instruments. While GLAST with its almost 2π FoV can provide very effective monitoring of a very large number of sources, 5@5 has an obvious advantage for the study of highly variable or transient γ-ray emitters. On the other hand, 5@5 is a detector with a small FoV, therefore it requires a special strategy of observations. Because of the overlap of the energy bands covered by these two instruments, GLAST may serve as a perfect "guide" for 5@5. All sources, that will be detected by GLAST, can be potential target for observations with 5@5. The second, more strategic motivation for the activity towards high altitude IACT arrays with energy threshold as low as several GeV is related to the lack of any realistic satellite-based alternative for GeV detectors in the the post-GLAST era. In this regard *the scientific reward of the implementation of ground-based approach in GeV gamma-ray astronomy will be enormous.*

Finally, a few comments concerning the large-field-of-view ground-based gamma-ray detectors. Three possible approaches have been proposed in this direction - (i) very large FoV imaging air Cherenkov telescope technique based on refractive optics [25], (ii) arrays of $15°$ FoV IACTs [26], and (iii) dense air shower particle arrays or large water Cherenkov detectors installed at very high, ≥ 4 km altitudes [27]. While the first two techniques require several technological innovations, the 3rd approach does not face serious technological challenges. The feasibility of both the high altitude air shower array and water Cherenkov techniques have been convincingly demonstrated by the Tibet and Milagro collaborations (see e.g. [23]).

The imaging atmospheric Cherenkov telescopes are designed for observations of γ-rays from objects with well determined positions. However, the high sensitivity of stereoscopic arrays coupled with relatively large field-of-view homogeneous imagers may allow quite effective sky surveys as well, as has been convincingly demonstrated by the *HESS* collaboration. The next generation GBGROs, in particular the $10^{-14}\ \mathrm{erg/cm^2 s}$ sensitivity *TeV* (sub) arrays will provide much deeper *all-sky* (not limited by the galactic plane) surveys. In particular, all point γ-ray sources with fluxes at the 0.01 to 0.1Crab flux level (depending on the energy band) can be be revealed within several steradians of the sky during one-year survey.

Nevertheless, the development of a ground-based technique allowing *simultaneous* coverage of a significant (1 steradian or so) fraction of the sky is a high priority issue. Actually the "standard" motivation for very large ground based gamma-ray detectors – *all sky surveys* – is a reasonable but perhaps not the strongest argument

in favor of such instruments. In fact, similar or even deeper *all sky surveys* can be conducted with the next generation IACT arrays. The strongest motivation of the "1 steradian FoV" detectors is, in fact, their unique potential allowing effective monitoring of γ-ray activity of a large number of highly variable sources like blazars and microquasars , as well as the possibility for independent detection and study of solitary GeV-TeV γ-ray events, both *related* (as GeV-TeV counterparts) and *not related* to classical (keV-MeV) GRBs. The particle acceleration and the secondary γ-ray production processes in compact objects proceed on extremely short time-scales, often with main energy release in the TeV band. Therefore the γ-ray emission carries unique information about the dynamics of these compact objects. *The promise of exciting discoveries of yet unknown VHE transient phenomena in the Universe fully justifies the efforts towards the construction of large field-of-view ground-based gamma-ray detectors*. Clearly, these instruments will be complementary to GLAST and the future large volume ("km^3" class) high energy neutrino detectors.

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